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THERMAL-FLUID ANALYSIS AND SIMULATION OF HIGH POWER SOLID-STATE LASER DIODE (SLD) ASSEMBLIES

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The thermal configuration is an important factor determining the successful operation of the high power solid-state laser diode assemblies. The solid-state diode array in an H-package using a conventional water-cooling flow was analyzed using a combined thermal and fluid finite element codes. A successful convergent solution was reached for the typical operation conditions. The results of the temperature and fluid velocity fields were reported and were compared reasonably with the experimental results.

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Thermal-Fluid Analysis and Simulation of High Power Solid-State Laser Diode Assemblies

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The ability to assemble low cost semiconductor lasers reliably as pump sources is essential to the success of all high-powered solid-state laser systems. Sources currently used are not reliable for high-energy operation when subjected to frequent on/off power cycling. The preliminary reliability study has indicated that turning the diodes on and off creates high thermal stress at the interfaces of the different materials used to accomplish the electrical connections and thermal management. The fatigue that occurs on the material interfaces resulting from the cyclic thermal stress significantly reduces the system's performance and lifetime. The study further indicated that high power pump sources with different thermal configurations might display different modes of failure mechanisms. The evidence suggested that a detailed investigation of the failure mechanism in conjunction with thermal and electrical models is needed. In the first step, a thermal-fluid model of solid-state laser diode arrays (SLDA) mounted on a heat sink assembly using conventional cooling techniques is developed using a computational fluid dynamics (CFD) solver in finite element numerical scheme.

The solid-state laser diode array (SLDA) in a H-package as shown in Fig. 1 is solved by the CFD solver. It contains six GaAs-based laser diode bars. Each bar has a width of 0.1 mm and a length of 10 mm. The cooling is done by circulating water in the copper cavity underneath the setting of the diode array. Two copper pipes connect to the bottom center of cavity shown in Fig. 1 are in-flow and out-flow pipes. The in-flow pipe has a smaller diameter of 5 mm inserted inside the out-flow pipe of 8 mm in diameter. The thickness of both pipes is 0.5 mm. The default operation condition of this device is that each laser diode is powered by 1.8 V and 68 Amps. When the cooling water in-flow rate is 1.2 liters per minute

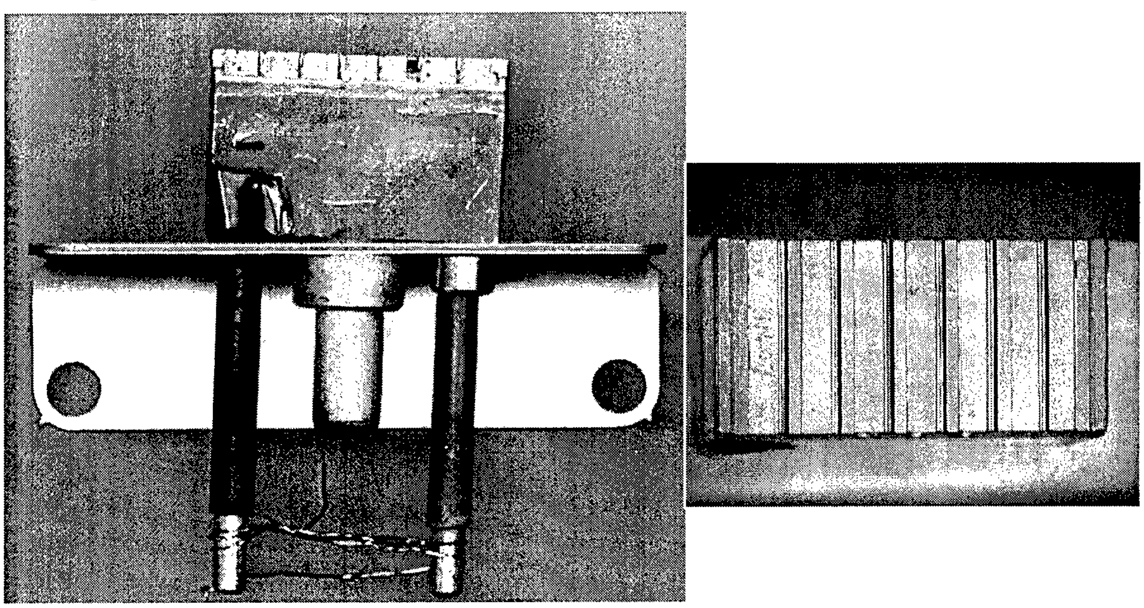

Fig. 1: H-Package and the top view.

(1.592 m/s) through a 4 mm diameter pipe, its minimum Reynolds number is about 6368. Therefore, this fluid flow problem has to be solved by a turbulence flow model. The physical properties for the water, air, and the materials in a H-package are function of temperature.

This fluid flow problem is solved using Flotran CFD solver in ANSYS, a general purpose finite element code. The fluid flow problem is defined by the laws of conservation of mass, momentum, and energy. These laws are expressed in terms of partial differential equations, which are discretized with a finite element based technique. The law of conservation of mass is defined by the continuity equation. The law of conservation of momentum is defined by momentum equations and the law of conservation of energy is defined by the energy equation. Linear constitutive equations are used for Newtonian flow. A temperature equation is used to solve the heat transfer problem. By solving the energy, momentum, continuity and heat transfer equation simultaneously, the temperature distribution in the solid and water and fluid flow velocity in the water can be obtained.

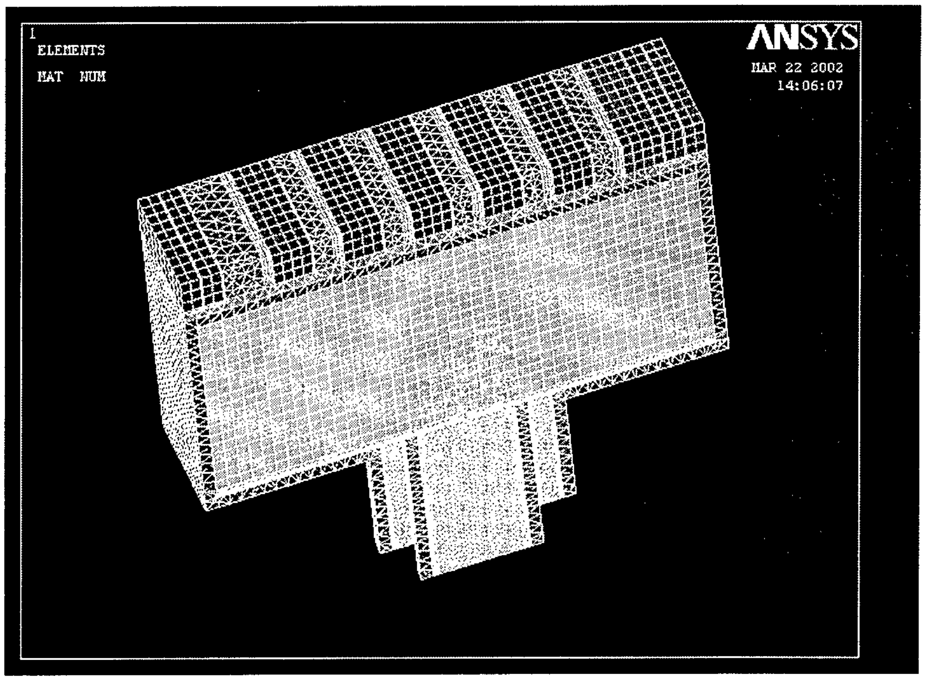

Fig. 2. Finite element model for a H-package.

Fig.1 is modeled by three-dimensional solid and fluid elements and its finite element mesh is shown in Fig. 2, where only half of the H-package is modeled due to its one-fold symmetry. Since the widths of the GaAs bar (0.1 mm), In solder (0.06 mm), air gap (0.15 mm), aluminum spacer (0.25 mm), and the thickness of the copper cavity (0.5 mm) are very small, this model needs to be assembled by large number of elements in order to obtained an accurate solution. A convergent and accurate solution can be obtained when this model is assembled by 98466 solid and fluid elements and 26621 nodes. A power density of 122.4×10^9 W/m^3 is applied to the six GaAs bars in this model. The power is cyclically turned on for 80 microseconds and then turned off for 320 microseconds until the operation is completed. Therefore, a transient analysis for the turbulence incompressible Newtonian flow is employed to solve this turbulence fluid flow model. The temperature of water on the bottom of the in-flow pipe is assumed to be room temperature at 300 K. The pressure of water on the bottom of out-flow pipe is assumed to be zero.

The maximum time step size is 80 microseconds when the power is turned on and is 320 microseconds when the power is turned off. It needs 2 time steps to complete a cycle of 400 microseconds. If this transient analysis takes 2 seconds to reach a steady-state, it requires 10,000 time steps. If each time step needs 15 iterations to reach convergent criteria, 150,000 iterations are needed for this transient analysis. For a model having 98466 elements and 26621 nodes, it takes a huge CPU time to complete this analysis. Since large data were generated each time step, our computer can only store data generated by few hundred time steps. Therefore, the transient analysis is solved for the first few hundred time steps and then restarts for next few hundred time steps. This restart process is repeated until 10,000 time steps are completed.

The first transient analysis starts from 0 to 0.16 second. The maximum temperature is located at node 24184 (on the top of the second GaAs bar from the right). Fig. 3 shows the maximum temperature distribution versus time from 0 to 0.16 second, where the temperature rises and drops cyclically between the upper and lower limit of the light blue band. When the power turns on, the temperature rises to the upper limit. When it turns off, the temperature drops to lower limit. For example, at 0.1592 second, the temperature is 325.122 K and the power turns on. After 80 microseconds at 0.15928 second, the temperature rises 1.568 K to 326.69 K and the power turns off. After 320 microseconds at 0.1596 second, the temperature drops 1.543 K to 325.147 K and the power turns on. After 80 microseconds at 0.15968 second, the temperature rises 1.567 K to 326.714 K and the power turns off. After 320 microseconds at 0.16 second, the temperature drops 1.543 K to 325.171 K and the power turns on. The results from 0.1592 to 0.16 second indicate a net rise of 0.024 K per power cycle.

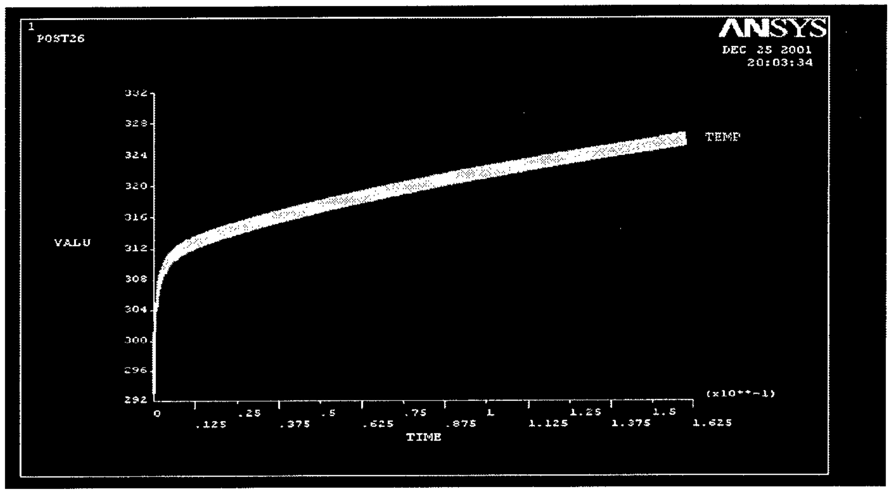

Fig. 3. . The temperature (K) at node 24184 in the laser diode cooling system versus time from 0 to 0.16 second

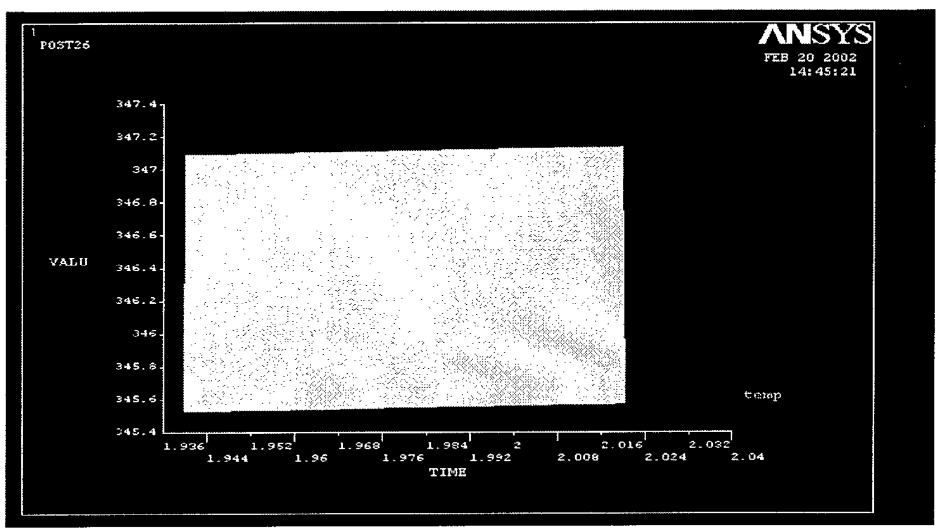

Fig. 4. The temperature (K) at node 24184 in the laser diode cooling system versus time from 1.94 to 2.02 second

The transient analysis reaches the steady-state at about 1.2 second. We will run the transient analysis to 2.02 second, where the steady-state is definitely reached. The location of the maximum temperature is shifted from node 24184 at 0.16 second to node 24247 (on the top of the right GaAs bar) at 2.02 second. Since Fig. 3 shows the temperature at node 24184 from 0 to 0.16 second, we will show the temperature at the same node from 1.94 to 2.02 second. Fig. 4 shows the temperature at node 24184 versus time from 1.94 to 2.02 second, where the temperature at the upper limit increases from 347.091 K at 1.93968 second to 347.136 K at 2.01968 second. The temperature at the lower limit increases from 345.528 K at 1.94 second to 345.573 K at 2.02 second. The net increase per cycle from 1.94to 2.02 second is 0.000225 K. Fig. 5 shows the temperature at node 24247 versus time from 1.94 to 2.02 second, where the temperature at the upper limit increases from 353.359 K at 1.93968 second to 353.426 K at 2.01968 second. The temperature at the lower limit increases from 351.791 K at 1.94 second to 351.859 K at 2.02 second. The net increase per cycle from 1.78 to 1.86 second for upper limit is 0.000335 K. Therefore the maximum temperature rise after 2.02 second of operation is about 53.5 K.

The flow velocity field essentially unchanged after time = 1.46 seconds. Fig. 6 shows a typical contour plot for flow velocity in z direction at 1.46 second. Fig. 7 shows a typical temperature contour plot at 2.01968 second.

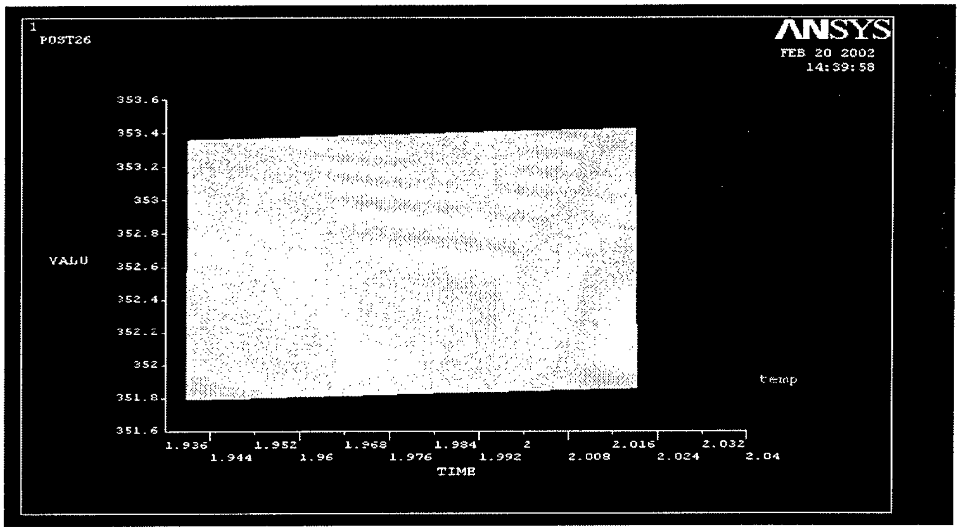

Fig. 5. The temperature (K) at node 24247 in the laser diode cooling system versus time from 1.94 to 2.02 second.

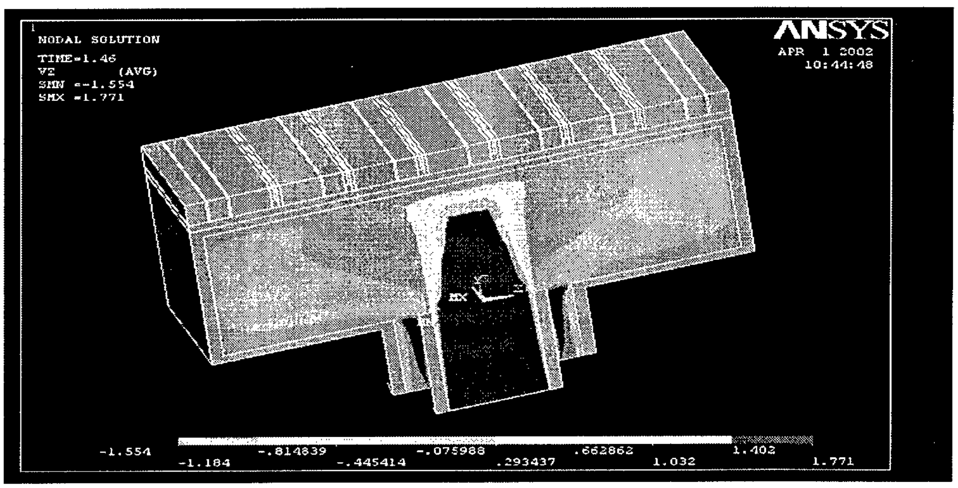

Fig.6. Flow velocity in z direction for the laser diode cooling system at 1.46 second.

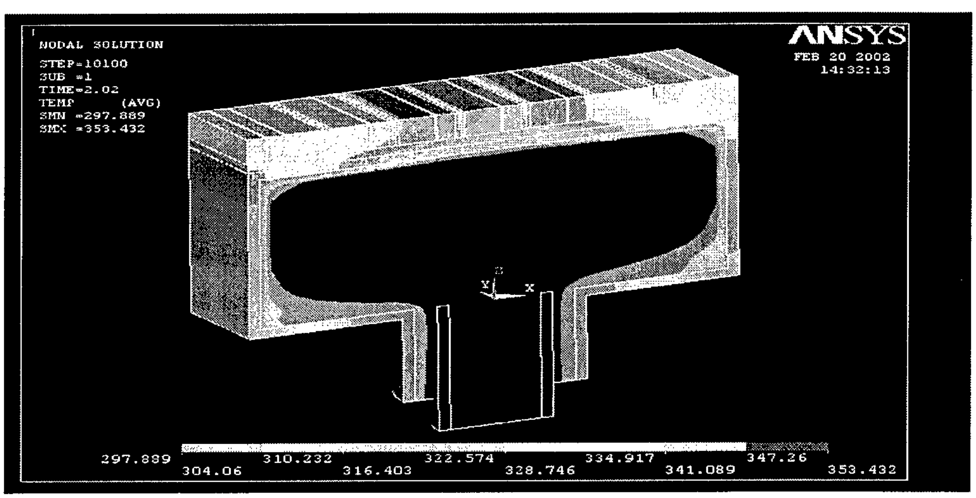

Fig.7. Temperature contour plot for the laser diode cooling system at 2.01968 sec.